LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-PROC-233190

Characterization of an AO-OCT system

J. W. Evans, R. J. Zawadzki, S. Jones, S. Olivier, J. S. Werner

July 31, 2007

Sixith Annual Workshop on Adaptive Optics for Industry and Medicine
Galway, Ireland
June 11, 2007 through June 15, 2007

Characterization of an AO-OCT system

Julia W. Evans[a,b], Robert J. Zawadzki[a], Steve Jones[b], Scot S. Olivier[b], John S. Werner[a]

[a] Vision Science and Advanced Retinal Imaging Laboratory,
Department of Ophthalmology & Vision Science,
UC Davis, 4860 Y Street, Suite 2400, Sacramento, CA, USA 95817

[b]Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore,USA 94550

evans74@llnl.gov

Summary

Adaptive optics (AO) and optical coherence tomography (OCT) are powerful imaging modalities that, when combined, can provide high-volumetric-resolution, images of the retina. The AO-OCT system at UC Davis has been under development for 2 years and has demonstrated the utility of this technology for microscopic, volumetric, *in vivo* retinal imaging [1]. The current system uses an AOptix bimorph deformable mirror (DM) for low-order, high-stroke correction [2] and a 140-actuator Boston Micromachines DM for high-order correction [3]. We are beginning to investigate the potential for increasing the image contrast in this system using higher-order wavefront correction. The first step in this analysis is to quantify the residual wavefront error (WFE) in the current system. Developing an error budget is a common tool for improved performance and system design in astronomical AO systems [4, 5]. The process for vision science systems is also discussed in several texts e.g. [6], but results from this type of analysis have rarely been included in journal articles on AO for vision science. Careful characterization of the AO system will lead to improved performance and inform the design of a future high-contrast system.

In general, an AO system error budget must include an analysis of three categories of residual WFE: errors in measuring the phase, errors caused by limitations of the DM(s), and errors introduced by temporal variation. Understanding the mechanisms and relative size of these errors is critical to improving system performance. In this paper we discuss the techniques for characterizing these error sources in the AO-OCT system. It is useful to first calculate an error budget for the simpler case using a model eye, and then add the additional errors introduced for the case of a human subject.

Measurement error includes calibration error, wavefront sensor (WFS) CCD noise, and sampling errors. Calibration errors must be measured by an external system. Typically this error is inferred from measurements of the point spread function (PSF). It can also be estimated by measuring known wavefront errors and comparing to the WFS measurement. Both methods will be used in the AO-OCT system. In this particular system measurement error introduced by the WFS can be caused by low light levels, poor camera sensitivity at the operating wavelength and noise introduced by heat in the uncooled CCD. Also, the gaussian beam profile of the system causes centroids near the edges of the pupil to be dimmer, and thus noisier. The easiest way to estimate measurement error is to compare successive wavefront measurements when the system is stable. This techniques will include vibrations and other systematic errors. Alternatively the measurement error can be estimated from measured signal to noise. This is more complicated but will decouple measurement errors from stability measurements.

Ultimately, even if the phase is measured perfectly, performance will still be limited by the fitting error [7]. This error is inversely proportional to the number of actuators of the DM. Basically wavefront errors with spatial frequencies greater than half the number of actuators across the aperture cannot be corrected. For DMs with modal influence functions (like the AOptix Bimorph in the AO-OCT system), this translates to the number of modes which can

be corrected. The AO-OCT system over-samples the wavefront, so to some extent, we can measure these out-of-band errors directly. In addition to fitting error, the DM will introduce errors based on the ability of each individual actuator to go to the position demanded by the control system. Generally this voltage step size is limited by the resolution of the drive electronics and can be calculated analytically.

Temporal variations in the system can be introduced by the limited bandwidth of the AO system or by systematic variations such as vibration on the optical table. These errors can be examined pixel by pixel in a time series of reconstructed wavefronts. The systematic errors are best examined with the model eye in a variety of situations, including with or without operating the scanners and with one or both deformable mirrors replaced with a flat. The scanners, deformable mirrors, temperature variations and vibrations in the optical system are all sources of systematic temporal variation. The best way to understand errors introduced by the limited bandwidth is to run the system at a higher bandwidth for comparison [8], which is impossible in most systems. However temporal power spectra can provide some indication of performance and are also useful in looking for systematic variations.

AO system characterization is an iterative process. Characterization of a system leads to changes in the system, which improve performance and require additional characterization. Error sources such as calibration and aliasing often require additional sensors, which may be difficult to install in an existing system, but some characterization can be done from an analysis of routinely collected data, or from data collected with a simplified system, where deformable mirrors have been replaced with flat mirrors and a model eye is used. A complete error budget is desirable, but even an incomplete one can lead to a greater understanding and improved system performance. The techniques discussed in this paper will be applied to the AO-OCT system and the preliminary results will be presented at the workshop.

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48. UCRL-ABS-230972. This research was supported by the National Eye Institute (grant EY 014743).

References

[1] R. Zawadzki, S. Jones, S. Olivier, M. Zhao, B. Bower, J. Izatt, S. Choi, S. Laut, and J. Werner, "Adaptive-optics optical coherence tomography for high-resolution and high-speed 3D retinal in vivo imaging," *Optics Express* **13**, pp. 8532–8546, 2005.

[2] D. A. Horsley, H. Park, and J. S. Laut, Sophie P. andWerner, "Characterization of a bimorph deformable mirror using stroboscopic phase-shifting interferometry," *Sensors and Actuators A: Physical* **134**, pp. 221–230, 2007.

[3] T. Bifano, P. Bierden, and J. Perreault, "Micromachined deformable mirrors for dynamic wavefront control," in *Advanced Wavefront Control: Methods, Devices and Applications II*, J. D. Gonglewski, M. T. Gruineisen, and M. K. Giles, eds., *Proc. SPIE* **5553**, pp. 1–16, 2004.

[4] M. van Dam, D. Le Mignant, and B. Macintosh, "Performance of the Keck Observatory Adaptive-Optics System," *Applied Optics* **43**(29), pp. 5458–5467, 2004.

[5] J. W. Evans, B. A. Macintosh, L. Poyneer, K. Morzinski, S. Severson, D. Dillon, D. Gavel, and L. Reza, "Demonstrating sub-nm closed loop MEMS flattening," *Optics Express* **14**, pp. 5558–5570, 2006.

[6] J. Porter, H. Queener, J. Lin, K. Thorn, and A. A. S. Awwal, *Adaptive Optics for Vision Science Principles, Practices, Design, and Applications*, Wiley-Interscience, 2006.

[7] J. W. Hardy, *Adaptive Optics for Astronomical Telescopes*, Oxford Series in Optical and Imaging Science, Oxford University Press, New York, 1998.

[8] L. Diaz-Santana, C. Torti, I. Munro, P. Gasson, and C. Dainty, "Benefit of higher closed–loop bandwidths in ocular adaptive optics," *Optics Express* **11**, pp. 2597–2605, 2003.